ADVANCED NATURAL GAS VEHICLE PROGRAM

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Abstract

The Johns Hopkins University Applied Physics Laboratory's (JHU/APL's) Advanced Natural Gas Vehicle (ANGV) Program, funded by the U.S. Department of Energy Office of Transportation Technologies and the Gas Research Institute, is a partnership of the Government, the University, and private industry. The goal of the ANGV Program is to advance the technology of compressed natural gas (CNG) onboard storage systems and to apply that technology in practical natural gas vehicle (NGV) prototypes. The first phase of the ANGV Program culminated with a prototype NGV compact sedan having a driving range in excess of 300 miles, ultra-low exhaust emissions, and the performance and trunk space comparable to those of gasoline-powered vehicles. This proof-of-concept prototype was developed by taking a systems approach to the integration of natural gas with the vehicle.

JHU/APL and Lincoln Composites are developing a 3600-psi service pressure CNG storage system called the Integrated Storage System (ISS) that uses carbon/fiberglass-overwrapped "pressure cells" encapsulated with an energy-absorbing foam in a container having an external appearance similar to a conventional gasoline tank. All associated valves, lines, and safety devices are integrated into a unit that is highly protected from physical impact. Trade-off and detailed design studies have been completed and prototypes have been burst, gunfire, and drop impact tested. The ISS reduces the cost, weight, and complexity of CNG storage, improves safety in a collision, and expands potential NGV applications.

With assistance (hardware and technical data) from Chrysler Corporation, the ANGV design tenets are now being applied to the mid-size Plymouth Breeze sedan. The ANGV-Breeze will use ISS technology for the CNG fuel storage, a state-of-the-art, multipoint, gaseous fuel injection system, and Chrysler's 2.4-liter DOHC engine optimized to operate on natural gas. After prototype development, the ANGV-Breeze will be field tested to evaluate real-world driving range, overall utility, performance, and acceptance by drivers.

Introduction

Half of the U.S. oil supply is now imported, compared to a third in the mid-1980s, and the U.S. Department of Energy is predicting nearly 60% dependency[1] by the year 2010. Domestic production continues to decline as U.S. oil reserves become more difficult to develop and international oil companies rely on easily extracted foreign oil. Further dramatic demands on worldwide petroleum production are predicted as motor vehicles proliferate globally from 500 million today to 1 billion by 2030.[2]

A viable alternative to petroleum for vehicle transportation is natural gas. More than 30,000 natural gas vehicles (NGVs) are being used in the U.S., but despite low fuel costs, reduced engine maintenance, and significant reductions in exhaust emissions, NGVs are "niche" vehicles restricted to fleets of trucks, delivery vans, buses, and taxis. This niche limitation is largely a result of the modest driving range between refuelings (about 150 miles), lost truck bed or automobile trunk space, and higher initial purchase cost due to the current state of compressed natural gas (CNG) storage technology.

The first phase of The Johns Hopkins University Applied Physics Laboratory's (JHU/APL's) Advanced Natural Gas Vehicle (ANGV) Program was to demonstrate a means for fully integrating CNG into a compact-sized automobile.[3] The project set five goals (Fig. 1): (1) to achieve a combined city/highway driving range of 300 miles, (2) to meet the California Air Resources Board's (CARB's) Ultra Low Emission Vehicle (ULEV) emissions standard, (3) to have acceleration performance on par with

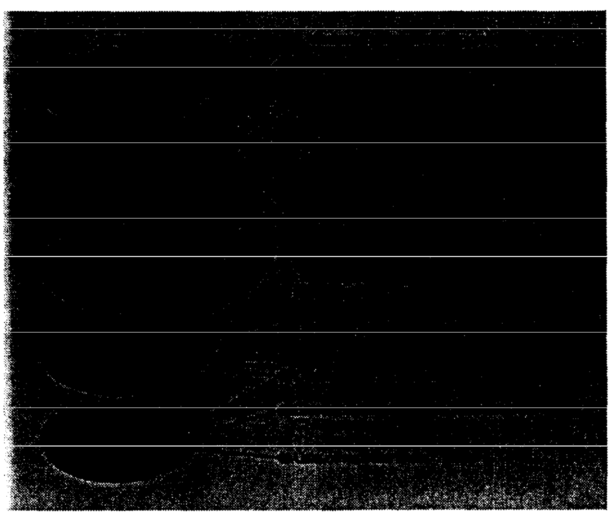

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Fig. 1. JHU/APL has identified five goals for the ANGV Program and the means for achieving those goals.

that of gasoline-powered vehicles, (4) to minimize the likelihood of significant CNG leakage in the event of a severe collision, and (5) to maintain at least 75% of the trunk space. As shown in Fig. 1, many of the lines between means and goals overlap, highlighting a synergism that can be achieved through a systematic design focused on the use of CNG. For example, one of the means for achieving the 300-mile driving range (e.g., small-displacement engine optimized for efficient combustion of natural gas) also helps meet the goal of low exhaust emissions.

The ANGV prototype incorporates the following changes into the baseline (OEM, original equipment manufacturer) vehicle (Fig. 2): (1) replacing the baseline engine with a small-displacement, high-compression engine tailored to natural gas fuel, (2) modifying the rear suspension and underchassis to create additional space for CNG storage, (3) using high-strength, lightweight, all-composite tanks arranged in a storage system designed with a high margin of collision safety, and (4) applying run-flat (built-in deflation support) tire technology. The following discussion provides additional information on these design changes and presents the characteristics of the prototype.

Engine Development

To achieve the range, performance, and emissions goals, the engine must make full use of the energy potential available in natural gas. In straightforward add-on conversions from gasoline to natural gas, there is generally a 10–12% loss in engine power as a result of the smaller charge of fuel for the stoichiometric combustion of natural gas. Increasing the compression ratio is the key to regaining higher specific output while simultaneously improving engine efficiency. Natural gas is well suited to high compression ratio operation because of its inherently high octane rating of about 130.

Working in conjunction with Chesapeake Automotive Enterprises of Reisterstown, Maryland, a small-displacement (1.6-liter), high-compression (12.7:1) engine was developed for the ANGV. The engine is based on the free-breathing, four-valve-per-cylinder design with a dual-path intake manifold and a central spark plug. Custom-developed high-compression pistons were incorporated to produce a crown-shaped combustion chamber for efficient natural gas combustion. Basic research on natural gas engines[4] has shown that the shape of the combustion chamber and the location of the spark plug are critical for efficient combustion.

A Gaseous Fuel Injection Controls, Inc., gaseous fuel injection system was tailored to the engine with support from the manufacturer. Ignition spark advance, control of the intake manifold runners, and management of exhaust gas recirculation were optimized for performance on a chassis dynamometer. Engine exhaust treatment uses a palladium/rhodium methane-specific catalytic converter.

The engine is mated to a four-speed automatic transaxle with driver-controlled overdrive. The powertrain provides both excellent performance and high fuel economy. The ANGV prototype has demonstrated city and highway fuel mileage of 27 and 38 mpg, respectively,

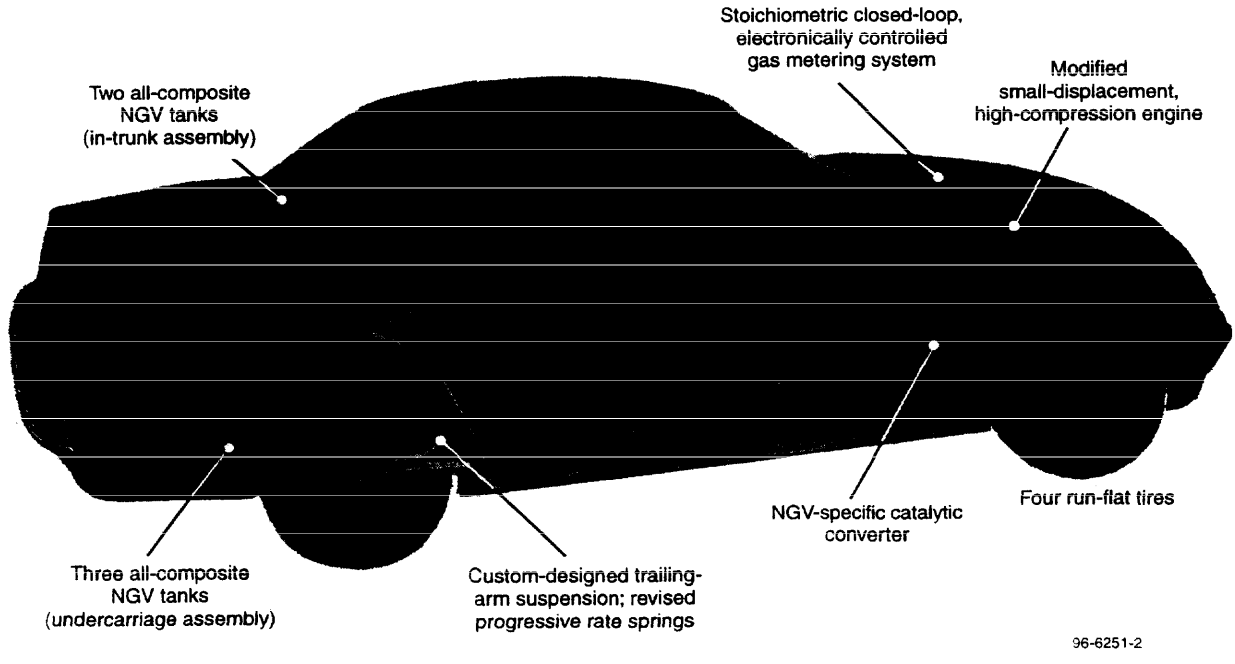

Fig. 2. Modifications made to the baseline vehicle for the ANGV Program.

in gallons of gasoline equivalent (124 standard cubic feet of natural gas equals 1 gallon of gasoline).

Rear Suspension and Chassis Modifications

To carry sufficient CNG on board for the 300-mile range, the undercarriage chassis space available for fuel storage was increased by (1) replacing the baseline lateral-link rear-suspension system with a custom-designed, trailing-arm suspension system and (2) replacing the spare-tire wheel well with a flat floor panel. The trailing-arm rear-suspension system eliminates lateral track bars and links, thereby increasing the open space between the rear wheels. The chassis rear frame provides a rigid structure for mounting the new suspension system. The redesigned rear suspension was developed to maximize compatibility with the baseline vehicle's spring and strut units and hub and brake assemblies. To offset the added weight of the natural gas storage cylinders, we used slightly longer rear springs to maintain ride height. Finite-element stress analysis of the suspension ensured a safe and lightweight design. Figure 3 is a computer-aided design (CAD) image of the essential components of the trailing-arm rear-suspension system, showing its physical relationship to the undercarriage CNG storage system. Figure 4 shows a test fit of the manufactured trailing-arm rear-suspension and undercarriage CNG storage system on a chassis mock-up.

Elimination of the spare tire increased chassis space for fuel storage. To compensate for the absence of a spare tire, the ANGV uses run-flat tires. These tires contain a built-in deflation support that enables the vehicle to be driven safely at highway speeds with no tire air pressure for up to 300 miles. A low-pressure warning system alerts the driver that a tire is operating in the run-flat mode. Goodyear Tire and Rubber Company of Akron, Ohio, custom manufactured Extended Mobility Tires™ for the ANGV prototype.

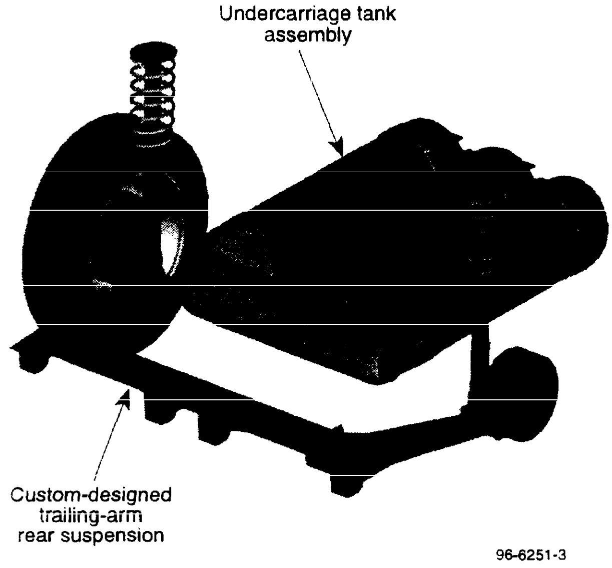

Fig. 3. Computer-aided design image of the trailing-arm rear-suspension and underchassis storage assemblies.

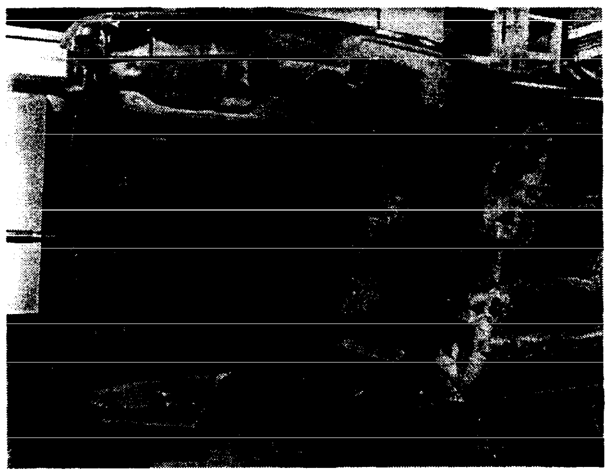

Fig. 4. Form/fit check of the trailing-arm rear-suspension and underchassis storage assemblies on the chassis mock-up.

Compressed Natural Gas Fuel Storage System

The ANGV fuel storage system comprises two assemblies: the undercarriage tank assembly and the trunk tank assembly. Each assembly uses steel brackets to group tanks (three for the undercarriage and two for the trunk tank assembly) together into a unit, stainless steel lines to interconnect the tanks, and manual isolation valves and an electrical solenoid valve to isolate each assembly from the fuel delivery system.

The JHU/APL-designed storage system adheres to safety specifications set by the NFPA-52 standard (National Fire Protection Agency/Compressed Natural Gas Vehicular Fuel Systems). The system uses all-composite tanks developed by Lincoln Composites[5] of Lincoln, Nebraska. The tanks are rated for 3600-psig operating pressure.

The all-composite, high-strength, lightweight tank features a high-density polyethylene liner, metallic end bosses, and an overwrap of a hybrid of carbon and fiberglass. The tanks have been qualified to the AGA/ANSI (American Gas Association/American National Standard Institute) NGV2 industry standard.

The storage tanks, themselves, are highly unlikely to leak in the event of a severe collision. The more likely source is the valves and lines associated with the storage and delivery systems. For that reason, a multiple-layered safety approach was developed that includes allowance for storage system movement in a severe collision, physical protection of valves and lines, and shut-off of the fuel delivery under certain conditions.

Vehicle Performance and Testing

After completing vehicle assembly, the ANGV prototype was road-tested to establish the following operating characteristics:

- The ANGV fuel capacity is 9.4 gallons of gasoline equivalent, with an overall fuel economy of 32 mpg for a range of 300 miles in combined city and highway driving.
- The trunk capacity of the ANGV is about 70% that of the baseline automobile, with most of the loss occurring in the space between the rear strut towers and under the package shelf. The curb weight of the ANGV is 240 lb more than that of the baseline automobile, with a slightly more rear-biased weight distribution of 57%/43% (front/rear).
- Handling and performance are similar to those found in most contemporary, front-wheel-drive compact sedans. The harshness of the ride increased when the vehicle was driven over rough road surfaces. The acceleration performance of 0 to 60 mph is a half second slower than that of the baseline automobile equipped with the same size engine and automatic transmission.

FTP (Federal Test Procedure) emission test data were compared with the 1994 Federal Standard and the California ULEV emissions standard (Fig. 5). These FTP results were obtained with the catalytic converter aged after about 4000 miles of driving. The prototype has been added to JHU/APL's autopool and has been driven for over 15,000 miles in the Baltimore/Washington corridor.

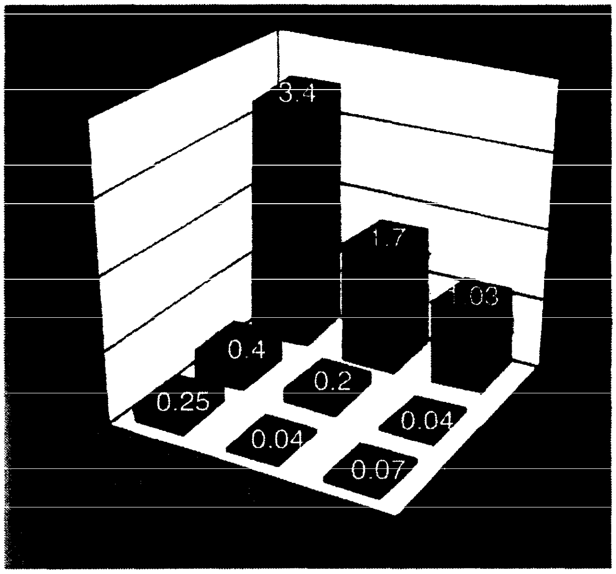

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Fig. 5. ANGV Federal Test Procedure exhaust emissions compared with U.S. and California ULEV standards for carbon monoxide (CO), oxides of nitrogen (NO_x), and nonmethane hydrocarbon (NMHC).

Integrated Storage System

Although the "strapped together tanks" approach filled the proof-of-concept need, the design was recognized as being far too complex, heavy, and costly to be production viable. This recognition led JHU/APL and Lincoln Composites to propose a novel concept of CNG storage called the Integrated Storage System (ISS). The basis of the ISS concept is the partitioning of the roles of pressure containment and damage tolerance and the optimization of each function through the use of composite materials and by the package design. The system structure consists of carbon/fiberglass-overwrapped "pressure cells" encapsulated with an energy-absorbing foam within a molded fiberglass shell. The thickness of the pressure-cell overwrap is based strictly on the need for gas containment and to prevent rupture in the event that the cell wall is penetrated while at service pressure (3600 psi). This differs from commercially available NGV2 tanks, which have an added amount of overwrap for damage tolerance from all sources. The ISS outer shell, in concert with the energy-absorbing foam, unitizes the pressure cells and provides protection from global and localized loads as well as from environmental exposure.

The ISS is treated as a single CNG container and as such has one manual valve, one solenoid, and a thermally activated pressure relief device all in an integrated package. The redundant components and added costs required by safety standards when multiple individual CNG tanks are mechanically strapped together are avoided by the new design. The entire ISS plumbing system is safeguarded from damage with a fiberglass protective cover that can be removed for service to the components. The protective cover also serves the dual role of capturing any leakage outgas and porting it to a safe area under the chassis. Another important ISS feature is its attachment to the vehicle by conventional straps. The use of straps provides the needed compliance to ensure that the automobile chassis' "crumple zone," designed by the OEM, is maintained in a severe, rear-end collision. A CAD solid-image assembly view of the ISS is depicted in Fig. 6.

The AGA/ANSI NGV2 safety standard gunfire test is the critical path in designing the pressure cells. This test assesses the ability of a container to withstand wall penetration damage, while at service pressure, without fragmentation (i.e., tank rupture). The test is conducted by pressurizing the container with nitrogen gas to its working pressure. The wall is penetrated with a 0.30-caliber

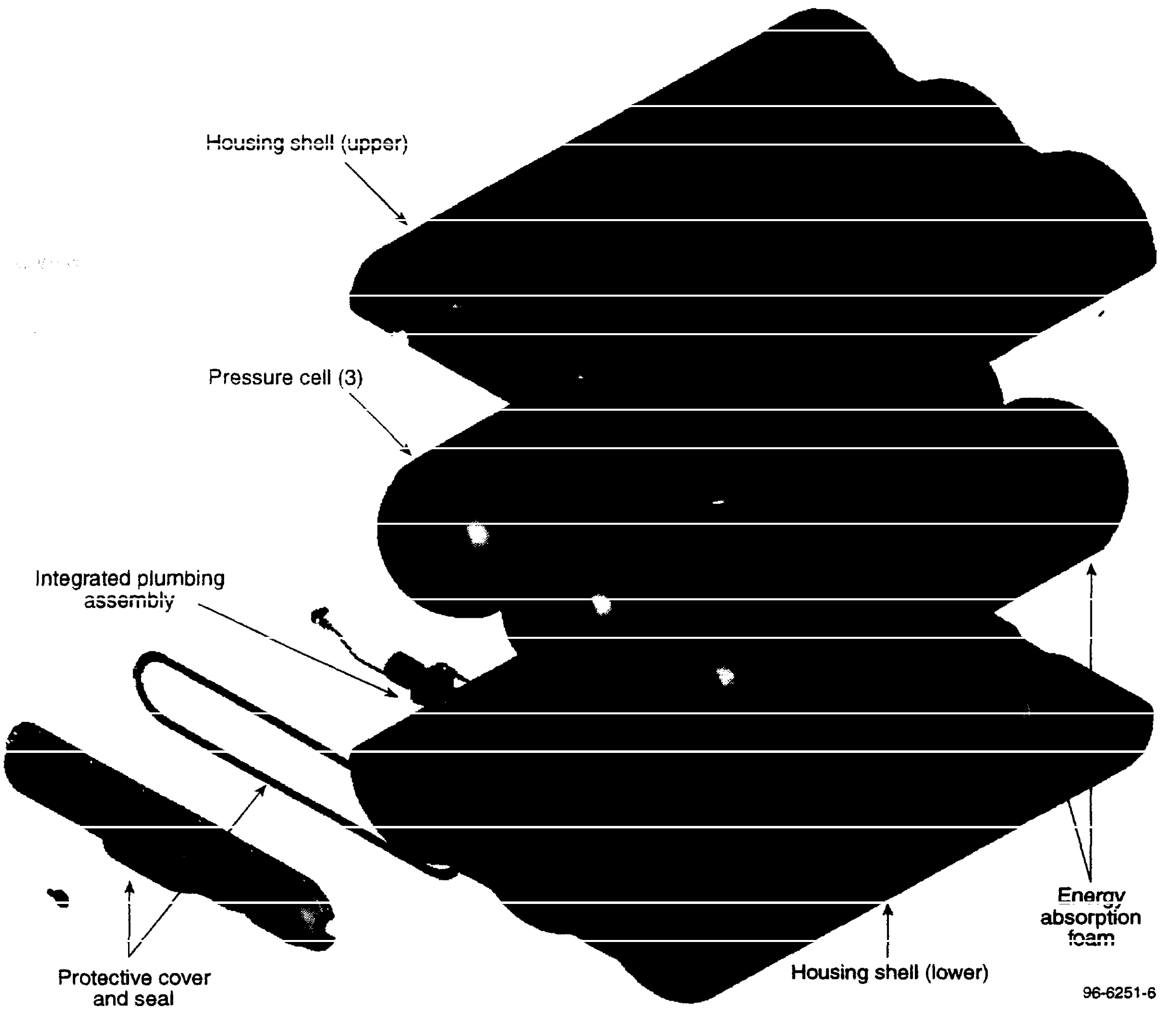

Fig. 6. Computer-aided design solid-image assembly view of the ISS.

armor-piercing bullet at an angle of 45° with respect to the cylinder axis.

Lincoln Composites completed three series of gunfire tests to establish the required factor of safety and carbon/fiberglass overwrap ratio for the ISS pressure cells. The three series of tests involved 19 pressure cells with a factor of safety ranging from 2.4 to 3.1 and carbon fiber percentage varying from 50% to 100%. The outcome of the gunfire test led to the conclusion that a 50/50 carbon/fiberglass hybrid was the optimum, low-cost overwrap design and the fiberglass makes a significant contribution to gunfire toughness. This conclusion is predicated by the limits of the overwrap parameters examined. The overwrap design process also used finite element analysis and netting analysis to establish the wall stress profile and support the laminate design.

Two other pressure-cell manufacturing developments involved processing improvements to reduce the high-density polyethylene liner wall thickness and miniaturizing of the aluminum end bosses. Figure 7 is a CAD solid-image, quarter-section view of the ISS pressure cell.

A design and manufacturing trade-off study was conducted by the JHU/APL Composite Section to optimize the ISS outer housing and energy-absorbing foam. Five design and manufacture options were explored from the perspective of tooling and unit part cost, design flexibility, and unit assembly. The outcome of the study was the selection of a split "suitcase" design formed using the low-cost Seeman Composites Resin Infusion Molding Process (SCRIMP). Drop weight impact tests were performed on fiberglass laminate coupons bonded to various energy-absorbing foams. The criteria for the foam selection were energy absorption, thermal stability, and dimensional recovery to account for pressure-cell growth and relaxation during refuelings. Woodbridge ENERFLEX™ polyurethane foam was chosen for its properties, low cost, and extensive automotive use history.

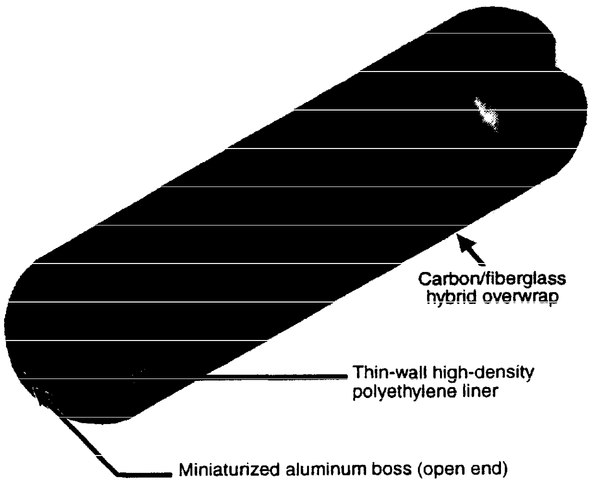

Fig. 7. Computer-aided design solid-image quarter-section view of the ISS pressure cell.

JHU/APL was also tasked with developing the ISS plumbing system and protective cover. Factors directing the plumbing design process were functionality, cost, reliability, satisfying safety requirements, and serviceability. A CAD image of the resulting design is shown in Fig. 8. The plumbing system was designed and is undergoing tests to meet the American National Standard, ANSI/AGA NGV3.1-1995, "Fuel System Components for Natural Gas Powered Vehicles," safety standard.

A pre-prototype ISS has been assembled, and an instrumented drop test was performed to assess compliance with NGV2-Revised Standard. This test is required to assess possible damage to the pressure vessel during shipping and handling or installation. This test is also vital in the ISS design to provide insight into the overall structural integrity of the container when it is subjected to a crash. The test is a series of vertical drops with different container aspect angles relative to the ground.

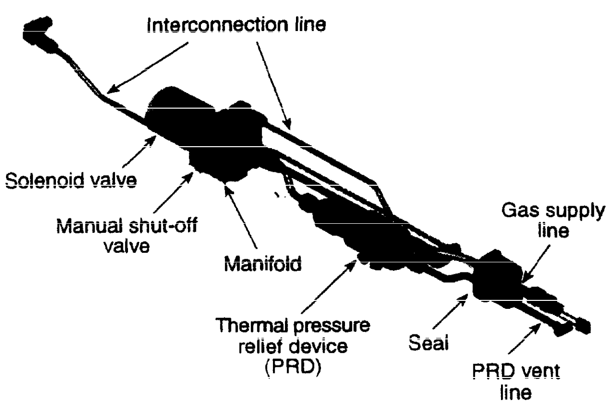

Fig. 8. Computer-aided design image of the ISS integrated plumbing assembly.

To date, the worst-case drop of 45° on the corner of the ISS has been performed from a height of 6 feet to the container's center of gravity. Inspection after the drop showed that the outer fiberglass shell had incurred some localized damage; the pressure cell, however, was undamaged. A more comprehensive series of safety qualification testing is scheduled for the latter part of 1996, including additional drop testing, bonfire testing, and further gunfire testing.

Future Plans

The long-range goal of the ANGV project is best expressed in the following statement of purpose:

"Align the ANGV project with a U.S. automaker. Demonstrate through prototyping that the ANGV design can be successfully applied to a mid-size sedan, maintaining performance, range, safety, and utility on par with comparable gasoline-powered vehicles while achieving ultra-low exhaust emissions. Work to assess the degree of consumer acceptance, compatibility with flexible assembly-line production, and worldwide market viability."

In working toward the first goal, Chrysler Corporation has agreed to support (in terms of automotive hardware) the project for development of the second-generation ANGV around the JA-series (Breeze, Cirrus, and Stratus) mid-size sedan. The second-generation ANGV will make use of the ISS technology and optimized conversion of Chrysler's 2.4-liter engine to natural gas. The Chrysler ANGV-Breeze will also include cast aluminum rear suspension trail-arms to reduce weight and enable low-rate production of the components at a reasonable cost. Goodyear Tire and Rubber will refine their Extended Mobility Tire™ to improve the balance between run-flat range and ride quality.

Figure 9 shows the planned ANGV programmatic activities and the approximate schedule of their development. Work has begun on optimizing the 2.4-liter engine, with the design of replacement high-compression (12.5:1) pistons using the internal engine modeling code KIVA-3 to explore alternative piston crown configurations. Custom forged-aluminum pistons will be fabricated, and the engine will be outfitted with a state-of-the-art multipoint gaseous fuel injection system developed by Chrysler Corporation. The objective is to match the power and torque of the gasoline-fueled engine while meeting or bettering CARB ULEV emissions. Work is also starting on designing the chassis modification for ISS integration.

In addition to the development of the ANGV prototype, a plan has been offered to evaluate crash-worthiness via simulation (i.e., DYNA3D) or an actual instrumented crash test (i.e., FMVSS-304) or both. The offered plan also ad-

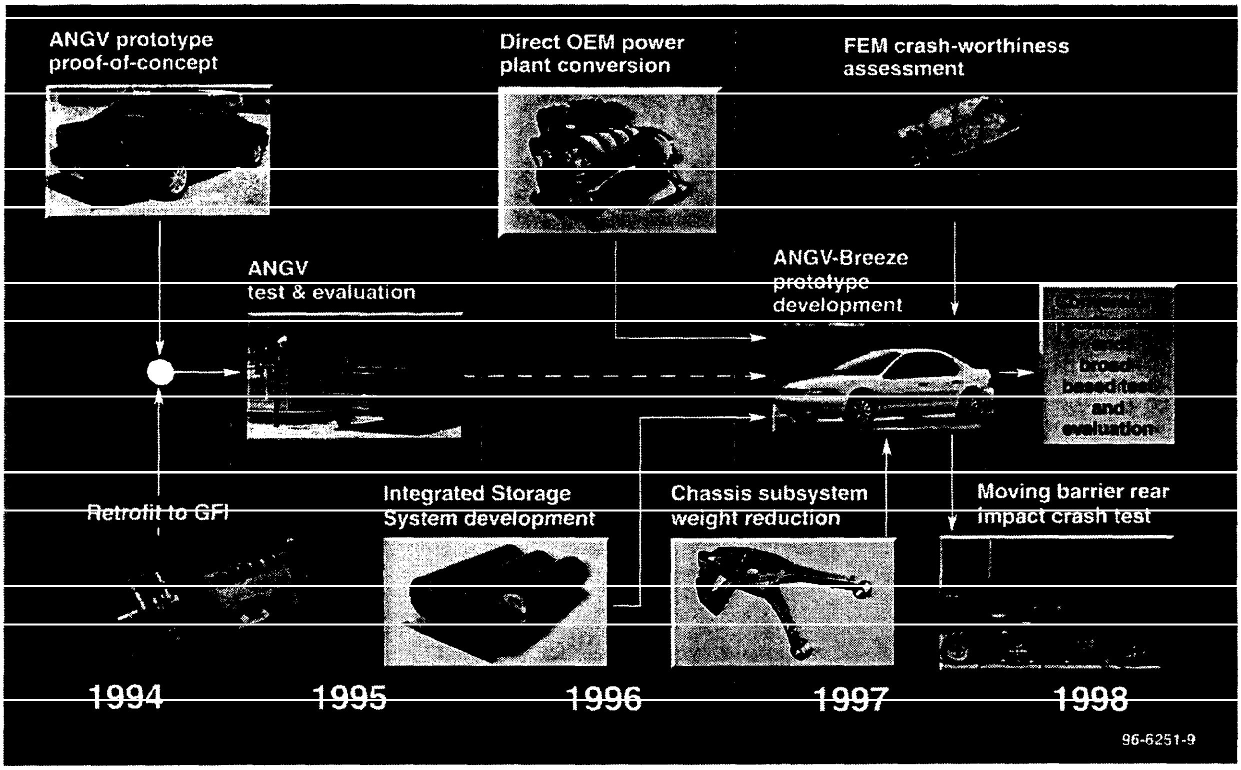

Fig. 9. The long-range program plan for the ANGV.

dresses the assembly of a small number of ANGV-Breeze prototypes for evaluation in selected fleets. Data would be collected on real-world driving range; overall utility, performance, and ride quality; and acceptance by drivers.

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